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13. ABSTRACT *(Maximum 200 words)*
This report summarizes the work and accomplishments of the University of Utah on the ONR grant #N00014-01-1-0033 entitled "A Statistical Approach To 3D Terrain Reconstruction". The report, as agreed with the Program Officer, Dr. L. Rosenblum, is the same as the presentation of the final meeting for this project, and consists of a series of slides with notes that explain the meaning of each slide. The report describes the motivation and overall goals of the project, presents results from this work, lists the publications that have resulted from this grant, and describes the mechanisms by which technology has been disseminated. This project addresses the question of surface reconstruction, particularly with the application of visualizing and analyzing terrain data. Results include fundamental developments in how to formulate the problem of surface fitting and smoothing and engineering developments, including fast algorithms on specialized hardware.

14. SUBJECT TERMS
Surface reconstruction, surface estimation, surface processing, laser range image, LADAR, level sets, tomography, volume graphics, partial differential equations, deformable models, surface segmentaiton, graphics processing cards, streaming architectures

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Surface Estimation and Analysis

Ross Whitaker
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ONR Final Report
September 19, 2003

Motivation

- Surface Measurement Technologies
  - LADAR, structured light, vision
  - Tomography
  - Sonar/ultrasound
  - Radar
- New computational capabilities
- Applications
  - Visualization – E.g command and Control
  - Recognition – Surveillance
  - Analysis

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This work addresses a changing technology landscape. There are lots of new and cheaper technologies for measuring surface shape, and some older technologies (such as MRI and tomography) can be treated as surface measurement mechanisms under certain circumstances. More memory and processor speed enable us to deal with surfaces and compute interesting things. Finally, there are new applications, driven by other technologies and capabilities.

3D Surface Reconstruction

- Noise
- Occlusions
- Geometric Distortion (Calibration)
- Registration

"Registration and Reconstruction from the China Lake Range Data", Whitaker and Juarez-Valdes, *University of Utah Technical Report*, 2001.

Data Courtesy U.S. Naval Air Warfare Center, China Lake, CA

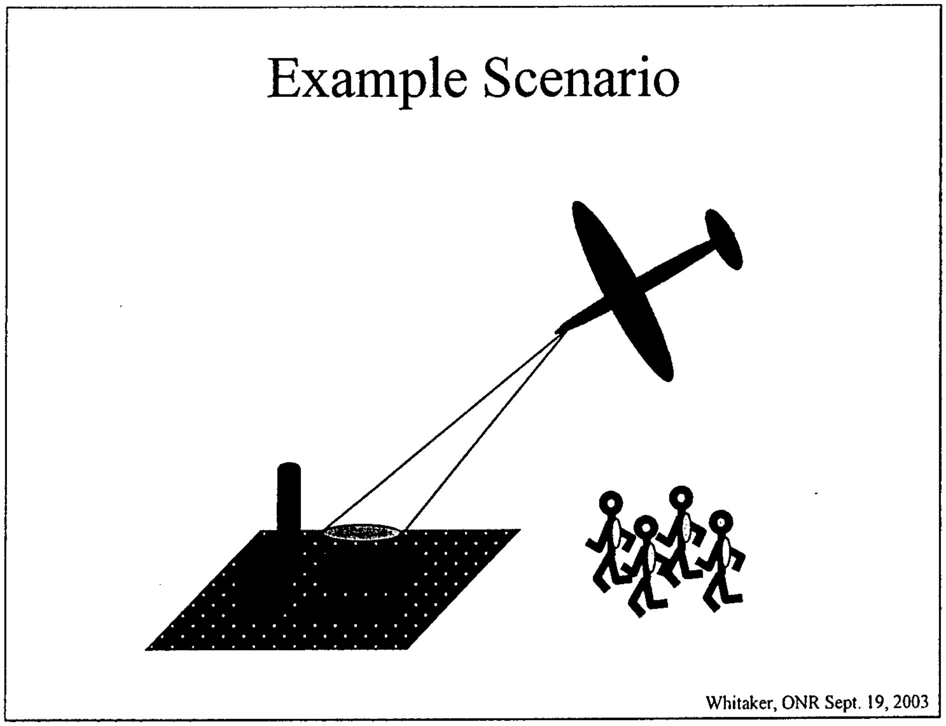
Whitaker, ONR Sept. 19, 2003

An example of NavAir data shows the issues with measuring surfaces. This is airborne LADAR data taken from about 1km. It has noise (random and systematic) and it has occlusions, so that even "rectification" does not produce a full 3D model. A reconstruction system should combine several such scans from different views and create a full 3D model.

Research Strategy

- Establishing the relationships between measured data and surfaces
  - Statistical foundation–estimation theory
  - Estimating surfaces directly form ladar/sonar/radar
- New priors – methods for smoothing/processing surfaces
  - Generalizing image processing to surfaces
- Surface representations
  - Extending level set technology for surface modeling
  - New algorithms/computational mechanism

This is how we structured our research. Some theory relating surfaces to data. Some better ways of filtering or smoothing surfaces. And some new ways of representing surfaces and performing the associated computation.



An example of how this type of capability could be used. Reconnaissance.

Major Results

- Surface estimation
  - Statistical formulation for surface reconstruction
    - Ladar and tomography
    - Freeform surfaces and parametric models
- Surface processing and analysis
  - Higher-order priors for surface reconstruction
  - General framework for mapping image processing algorithms to surface
- Level-set surface modeling
  - New algorithms for fast propogation/tracking of interfaces
  - New computational scheme for higher-order flows

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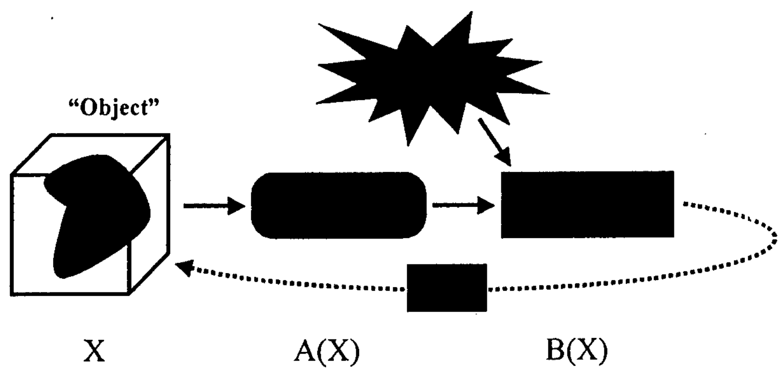
Here are the results that came out of this project. All of these results have associated published papers and software.

Surface Estimation

A Systems Approach



Bayesian reconstruction: maximizing the posterior – likelihood (data) + prior

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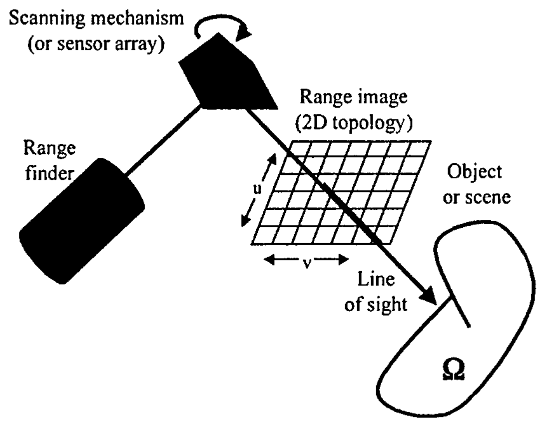
This is the big picture of how to formulate the problem of "estimating" surfaces from noisy data. This is an extension of a philosophy which has been pursued with some success in the image processing literature. This is a Bayesian formulation where the surface is meant to optimize the statistical relationship between the data (likelihood) and what we know about shapes in the world (prior).

Surface Estimation from Ladar

- Scanner Model
  - Geometry
  - Lines of sight
  - Pose
- Sensor Model
  - Noise
  - Gaussian w/outliers
- Shape Optimization
  - Parameters
  - Free-form



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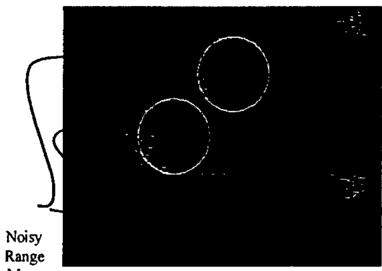
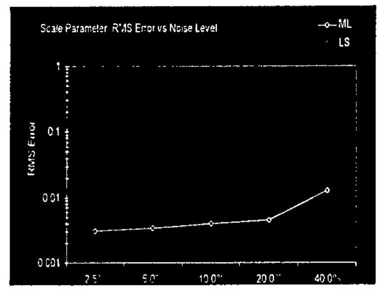
This is the "sensor model" it describes how, given a surface, a particular measurement would be produced. A typical ladar (laser range finder) takes a 2D array of measurements. Each measurement corresponds to a line of sight and gives a distance to the nearest surface, with some random noise. Studies of such instruments [Gregor and Whitaker, 2002] show that a Gaussian noise model with outliers is a good model. If we assume the measurements are independent, then we can quanify the "likelihood" of a particular surface, conditional on a set of range measurements.

Estimating 3D Surface Parameters Via Maximum Likelihood





- Converges more reliably and more accurately than ICP.
- Unbiased!

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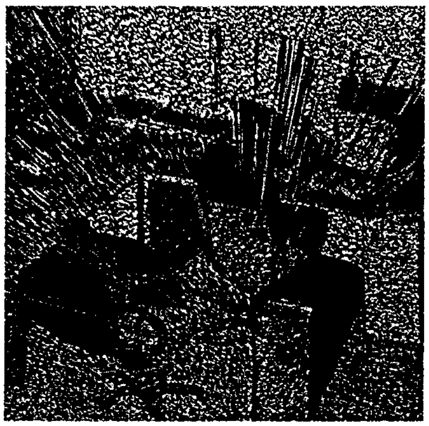
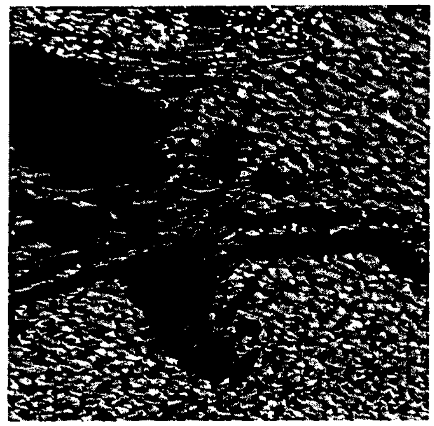
If we change the parameters of a surface (e.g. its orientation and size), we can try to find the surface that gives the best estimate of likelihood. This is a maximum likelihood estimator. Statistical theory says that this estimator is "unbiased", which means on the average, it gives the correct answer. Using this estimator we can align models to range measurements. This slide shows some experiments in 2D to confirm that this is a reliable, accurate way to fit surfaces to range data. It does significantly better than the conventional approach (closest point error), which is biased.

Surface Estimation

Example: Ladar Data From Indoor Scene



Surface Rendering of Single Scan



Close Up View

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This is some example rage data. It is rendered as a surface. The triangles are constructed by connecting nearby points in the range image. This data is noisy. A closeup of the legs of the chair shows how little information is containted there.

Registration of Ladar Data

- Complex scenes w/noise
  - Improved accuracy and convergence

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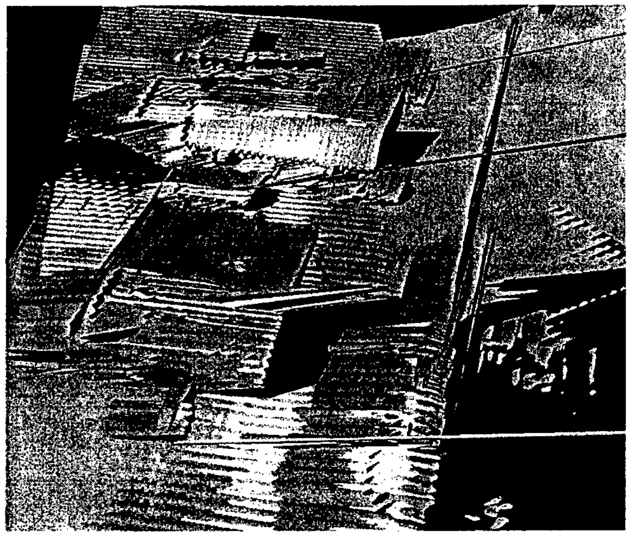
One of the big problems of constructing 3D models from range data is determining the relative position of the scans. Typically external approaches such as GPS or dead reckoning are not accurate enough to get good 3D reconstructions. Thus, people often rely on data-driven approaches for aligning different scans. We can use this maximum-likelihood approach for aligning mdoels to data for registering one range map to another. The results proved to be very robust, even for complicated scenes such as that shown here (one scan rendered in white the other in magenta).

China Lake Data Registration



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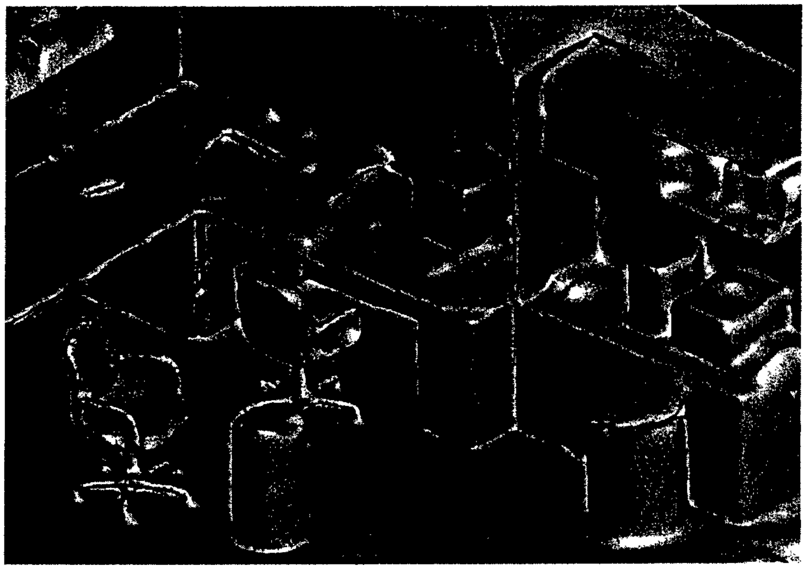
This an example of four different scans, taken from different point of view, registered into one coordinate system.

Surface Reconstruction



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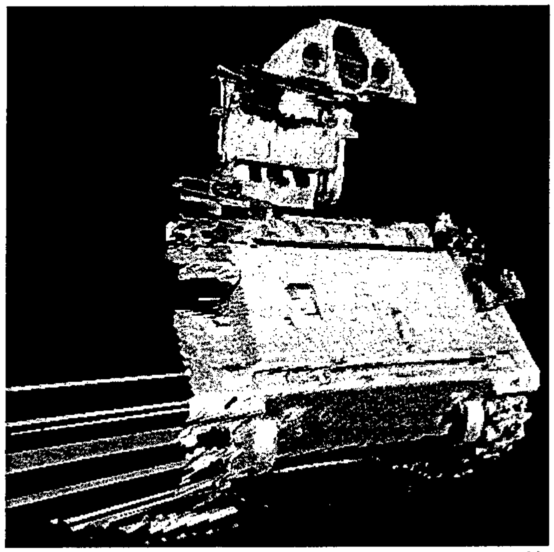
Once we have sets of registered scans, we can fit free-form surface models (using the same statistical approach) to multiples scans to get 3D models of complex scenes. In this case the models are represented volumetrically as level sets and the surface estimation includes a prior (to be describe more later) that prefers smooth surfaces with sharp creases. This reconstructed includes ten scans from different points of view.

Deltasphere LADAR Scan



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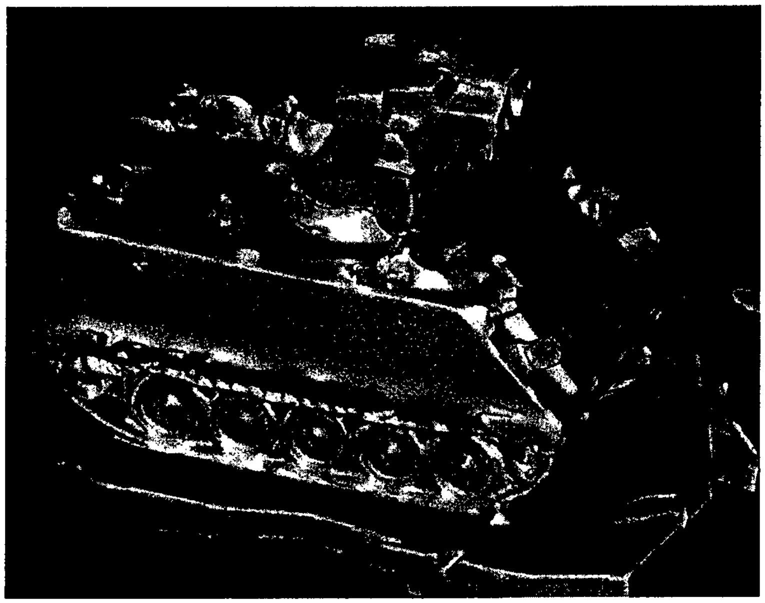
This is data from the 3rd Tech Delta Sphere scanner.

Volumetric LADAR Reconstruction



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A reconstruction from eight range images.

China Lake Reconstruction

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Reconstruction from the China Lake data set.

China Lake Reconstruction

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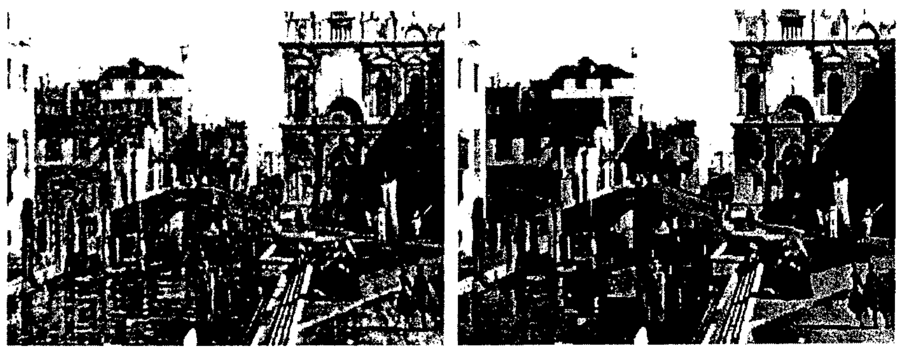
Higher-Order Surface Processing
Feature-Preserving Flows

- Image Processing
  - E.g. anisotropic smoothing (Perona & Malik)



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Part of the technology which makes this possible is a generalization of ideas from image processing. Using PDEs that penalized gradients of the image, people have been able construct nonlinear filters that smooth images and enhance strong edges. These terms can be used as "priors" and combined with a likelihood (data fitting) term to do reconstruction. One of our goals was to do this for surfaces.

Strategy

- Variational formulations of curvature
  - Generalization of grad mag from IP
  - Gradient of normal map
  - Allowance for outliers
- Decouple the normals from surface
  - Process normals
  - Refit surface to normal map
  - System of 2nd-order equations

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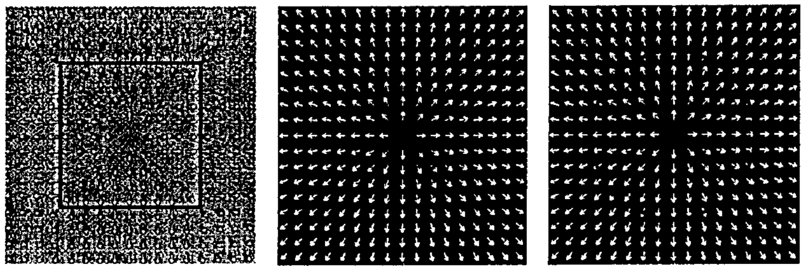
The strategy for surfaces is to construct energy functionals that rely on penalizing the gradients of the normals, which live on the surface. If this is formulated correctly, the results will be "geometric", which means they depend only on the shapes of the objects and not the parameterization or coordinate systems that one uses. The resulting PDEs are not easy to solve, because they include fourth-order derivatives. We have proposed a strategy that simultaneously smooths the normals of the surface while trying to keep the surface aligned with those normals.

Surface Filtering Strategy



Surface & Normals Process Normals Refit Normals

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This is an example of how this computational strategy works. A shape induces a field of normals which are consistent with the surfaces nearby. We can smooth those normals (maintaining unit length). Then we can refit the surface. In this case a square would get "blurred" to a circle, which is a steady state of this process.

Anisotropic Diffusion

Original model

Anisotropic 4th order smoothing

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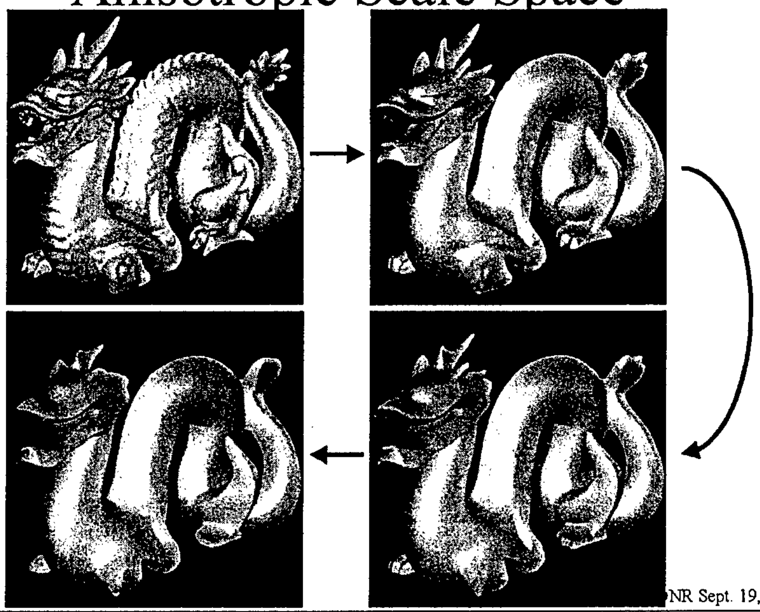
If we use a penalty function on the gradient of the normals that allows for outliers, analogous to Peronal&Malik for images, we obtian flows that smooth surfaces while enhancing strong creases.

Anisotropic Scale Space



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Just like with images, this produces an anistropic scale space, or a series of "cartoon-like" shapes which produces simpler objects that retain the important features.

Surface Analysis

- In the context of models for AR
- "It would be great if a soldier knew how man steps it would take to get from building A to vehicle B"
- Segmentation, hierarchical grouping, ...
- Low level -> high level

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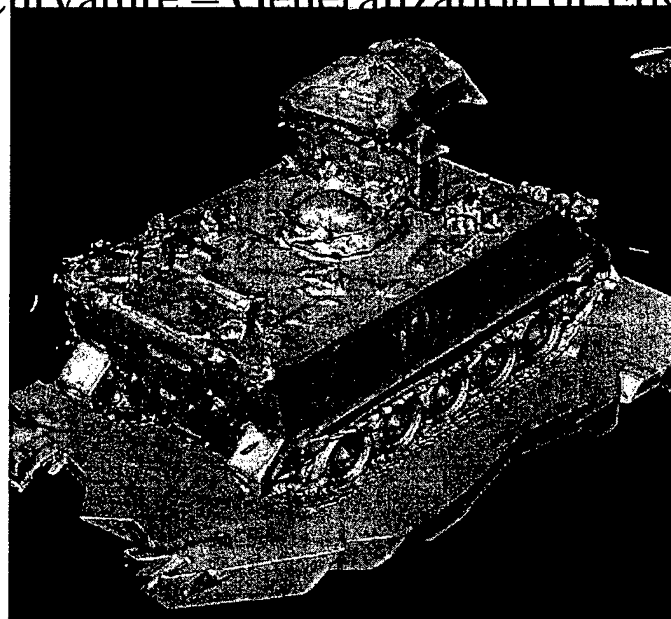
One of the goals of this work is to produce segmented surfaces that could be used for analysis. Thus, using generalizations of ideas from image processing, we can partition surfaces into meaningful pieces.

Curvature – Generalization of Edges



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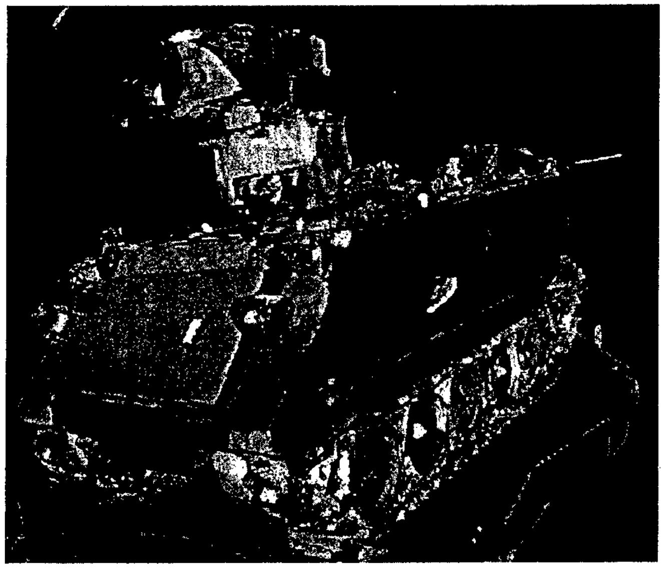
The "edges" of surface patches are places where the gradient of the normals (I.e. curvature) is high.

Watershed Segmentation



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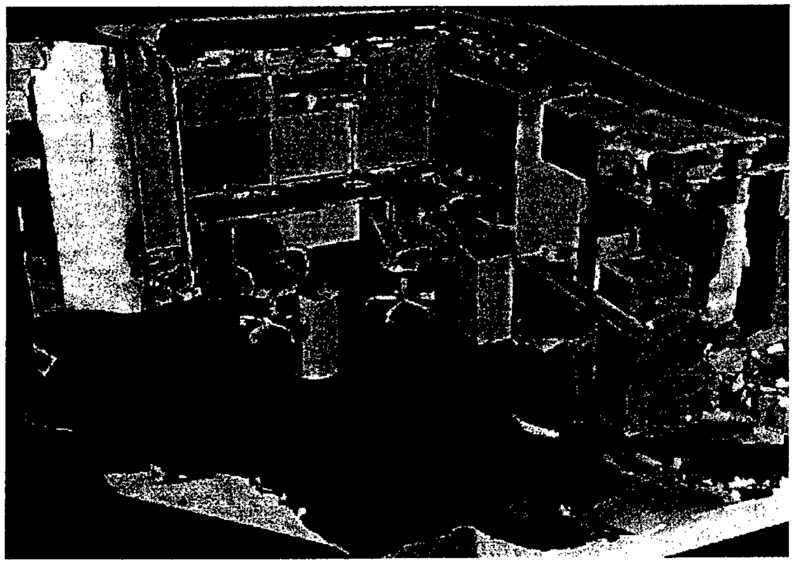
Using watershed segmentation we can produce a hierarchy of surface patches, which can be used to decompose a model into its constituent parts.

Watershed Segmentation



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Watershed Segmentation

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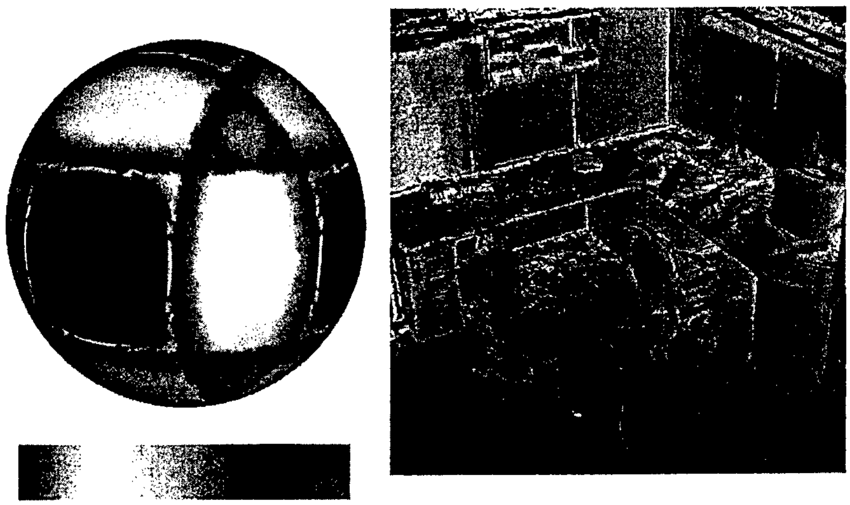
Cramer-Rao Bounds

A Statistical Estimate of Reconstruction Quality



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Because we are using statistical formulations, we can rely on ideas from signal processing to compute error bounds. This is a generalization of Cramer-Rao bounds, which is typically used for putting error bounds on parameter estimates. In this case we have applied it to shape, to give us bounds on the position of the surface in the direction of the normal. This ties back into the sensor model. Thus, a particular range image, reduces the error of the surface in a way that depends on the noise in the measurements and the direction from which it is taken.

Processing Height Fields

- Formulation of higher-order smoothing for 2.5D surfaces
- Surface deformation gives PDE on image
- Appropriate for terrain processing
- Preprocessing + detection

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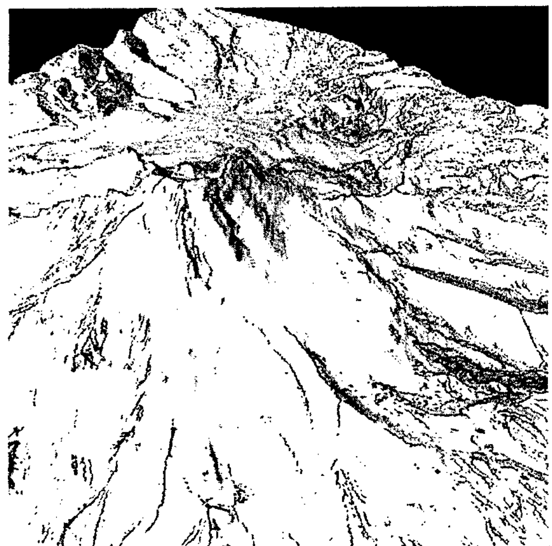
Some applications done require full 3D surfaces, but rather height fields, in which one parameter is a function of the other two. This is useful, for instance, in dealing with terrain maps.

Terrain Analysis

Contour-Line Vertices – Ridges and Valleys

- Zero crossing of *third-order* differential quantities
- Noise and small-scale structure dominates
- Generally difficult to tune blurring, thresholds, etc.
- Too-many features + broken lines



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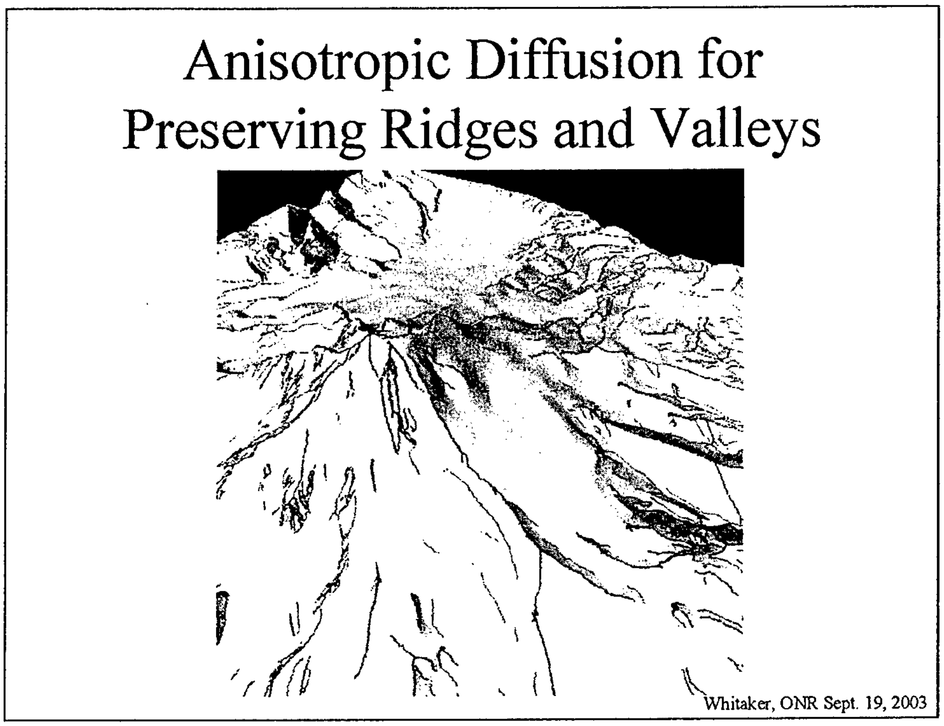
For instance, one of the things people want to do with terrain data is detect features, such as valleys and ridges. This is useful, for instance, for compression. Valleys and ridges are indicated by high curvature in the contour lines. Detecting these requires third-order deratives, which are noisy. Preprocessing can help this.



The same ideas used for level-set surfaces, which smooth data while preserving creases, apply to height fields, improving the detection of features.

Overcoming The Computational Burden Interactive, 3D, Deformable Models

- Nonlinear PDE – Iterative over volume
- Algorithms: front-tracking schemes
- Hardware:
  - Clusters and multiprocessors
    - Scalable
  - Commodity graphics cards
    - Price to performance
    - Rate of improvement – specialized processors

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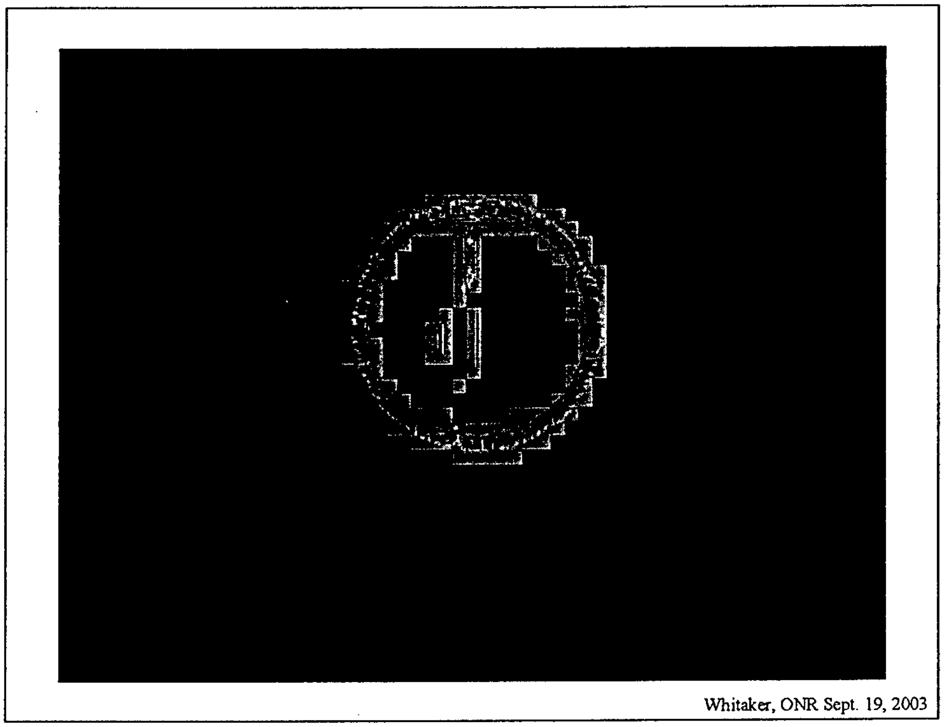
Many of the methods developed in this work require solutions to nonlinear PDEs, which can be computationally expensive. Part of the work is the development of methods for solving these problems more quickly. We have researched two approaches, one using multiprocessors on large super computers (e.g. SGI Origin series) and the other using comodity graphics cards (GPUs). Both approaches have been sucessful, but the GPU approach is more practical for a wider range of potential applications.

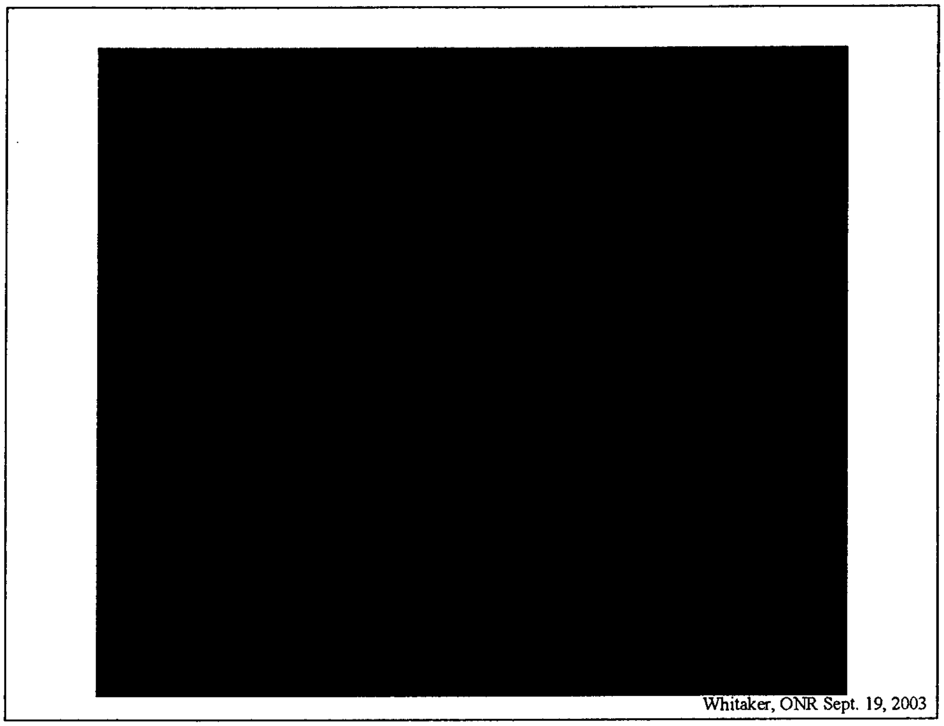
Solution: Graphics Processor

- Why?
  - Data level parallelism
  - High speed memory
  - Computation power going up quickly
  - Inexpensive ($400 vs. $50,000+)
- Issues
  - GPUs – SIMD processors, limited capabilities
  - Programming interfaces primitive
  - Limited GPU-CPU bandwidth/speed

GPUs are cheap and their power is increasing rapidly. They represent an example of a "streaming architecture", which privides homogeneous, fine-grained parallelism (SIMD) with very high bandwidth to memory. Thus they are particularly well suitedfor solving PDEs on large grids.



This video shows a slice of a 3D model as it evolves on the GPU. The greyscales indicated curvature values and the little squares are "tiles" which allow us to focus the GPU processing only on those areas of the computational domain that are near the moving wavefront, which is associated with the level-set PDE.



This is an demo of an application for 3D segmentation using level-set based deformable models. The audio describes the specifics.

Publications

- R. Whitaker, "A level-set approach to 3D reconstruction from range data", *International Journal of Computer Vision*, 29(3), Oct. 1998, pp. 203–231.
- D. L. Elsner, R. Whitaker, and M. A. Abidi, "Volumetric modeling of objects and scenes using range
- images," *Digital Signal Processing: A Review Journal*, 9(2), April 1999, pp. 120–135.
- A.Mangan, R.Whitaker, "Partitioning 3D surface meshes using watershed segmentation", *IEEE Trans. on Visualization and Computer Graphics*, 5(4), Dec. 1999, pp. 308–321.
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- J. Gregor, R.Whitaker, "Indoor scene reconstruction for sets of noisy range images", *Graphical Models* 63(5), Sept. 2002, pp. 304–332.
- R. Whitaker, E. L. Valdes-Juarez, "On the reconstruction of height functions and terrain maps from dense range data", *IEEE Trans. on Image Processing*, 11(7), 2002, pp. 704–716.

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- R. Whitaker, J. Gregor, "A maximum likelihood surface estimator for dense range data", IEEE Trans. on Pattern Analysis and Machine Intelligence, 24(10), October 2002, pp. 1372–1387.
- R.Whitaker, V. Elangovan, "A direct approach to estimating surfaces in tomographic data", *Journal of Medical Image Analysis*, 6(3), 2002, pp. 235–249.
- T. Tasdizen, R. Whitaker, P. Burchard, S. Osher, "Geometric surface processing via normal maps", To appear: *ACM Trans. on Graphics.*
- T. Tasdizen, R. Whitaker, "Higher-Order Geometric Surface Priors for Surface Estimation", IEEE Trans. on Pattern Analysis and Machine Intelligence, To appear.
- A. Lefohn, J. Kniss, C. Hansen, R. Whitaker, "GPU-Based Interactive Level Sets for Volume Visualization and Analysis", IEEE Trans. on Visualization and Computer Graphics, To appear.

Publications (Conferences)

- R. Whitaker, D. Breen, "Level-set models for the deformation of solid objects," *in Proceedings of Implicit Surfaces '98*, Eurographics/Siggraph, June 1998, pp. 19–35.
- R. Whitaker, J. Gregor, and P. Chen, "Indoor scene reconstruction from sets of noisy range images", *Second International Conference on 3-D Digital Imaging and Modeling*, Oct. 1999, pp. 348–357.
- R.Whitaker, "Reducing aliasing artifacts in isosurfaces of binary volumes", *IEEE Volume Visualization And Graphics Symposium*, 2000, pp. 23–32.
- R. Whitaker, Xinwei Xue, "Variable-conductance, level-set curvature for image denoising", IEEE International Conference on Image Processing, October 2001, pp. 142–145.
- R. Whitaker, "Reconstructing terrain maps from dense range data", IEEE International Conference on Image Processing, October 2001, pp. 165–168.
- A. Gothandaraman, R.Whitaker, J. Gregor, "Total variation for the removal of blocking effects in DCT based encoding", IEEE International Conference on Image Processing, October 2001, pp. 455–458.

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- T. Tasdizen, R. Whitaker, P. Burchard, S. Osher, "Geometric Surface Smoothing via Anisotropic Diffusion of Normals", *Proc. IEEE Visualization 2002*, pp. 125–132.
- K. Museth, D. Breen, R. Whitaker, A. Barr, "Level-Set Surface Editing Operators", in *SIGGRAPH 2002*, pp. 330–338.
- A. Lefohn, J. Kniss, C. Hansen, R. Whitaker, "Interactive GPU-Based Level-Set Models for Volume Visualization and Analysis", Proc. IEEE Visualization 2003, To appear.
- A. Lefohn, J. Cates, R. Whitaker, "GPU-Based Level-Set Models for Brain Tumor Segmentation", Proc. Medical Image Computing and Computer Aided Interventation 2003, To appear.
- T. Tasdizen, R. Whitaker, "Cramer-Rao Bounds on Surface Estimation", Proc. 3Dim 2003, To appear.
- T. Tasdizen, R. Whitaker, "Higher-Order, Feature-Preserving Priors for Surface Estimation", Proc. 3Dim 2003, To appear.

Tech Transfer – Software

- VISPack
  - C++, object-oriented toolkit
  - Image/volme processing, level-set solvers
  - Several hundred downloads, mostly academics
- Insight Toolkit
  - NIH/NLM Sponsored
  - First release this fall – thousands of downloads/month
  - Ported most of the level-set and reconstruction algorithms developed under ONR project
  - E.g. recent contract for fourth-order surface flows

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Workshops That Presented This Work

- "Beyond Blobs" SIGGRAPH, 2003
- "Image Processing for Volume Graphics" SIGGRAPH 2002
- "Beyond Blobs" SIGGRAPH, 2002
- "PDEs for Graphics and Image Processing" SIGGRAPH, 2002
- "Image Processing for Volume Graphics" IEEE Visualization, 2002
- "Image Processing for Volume Graphics" SIGGRAPH 2001
- "Image Processing for Volume Graphics" IEEE Visualization, 2001

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Students and Post-Docs

- Alan Mangan
- Xinwei Xue
- Ernesto Juarez
- Suyash Awate
- Vidya Elangovan
- Tolga Tasdizen

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